Calibration of the CMS hadron calorimeters with proton-proton collision data at $\sqrt{s}$ = 13 TeV

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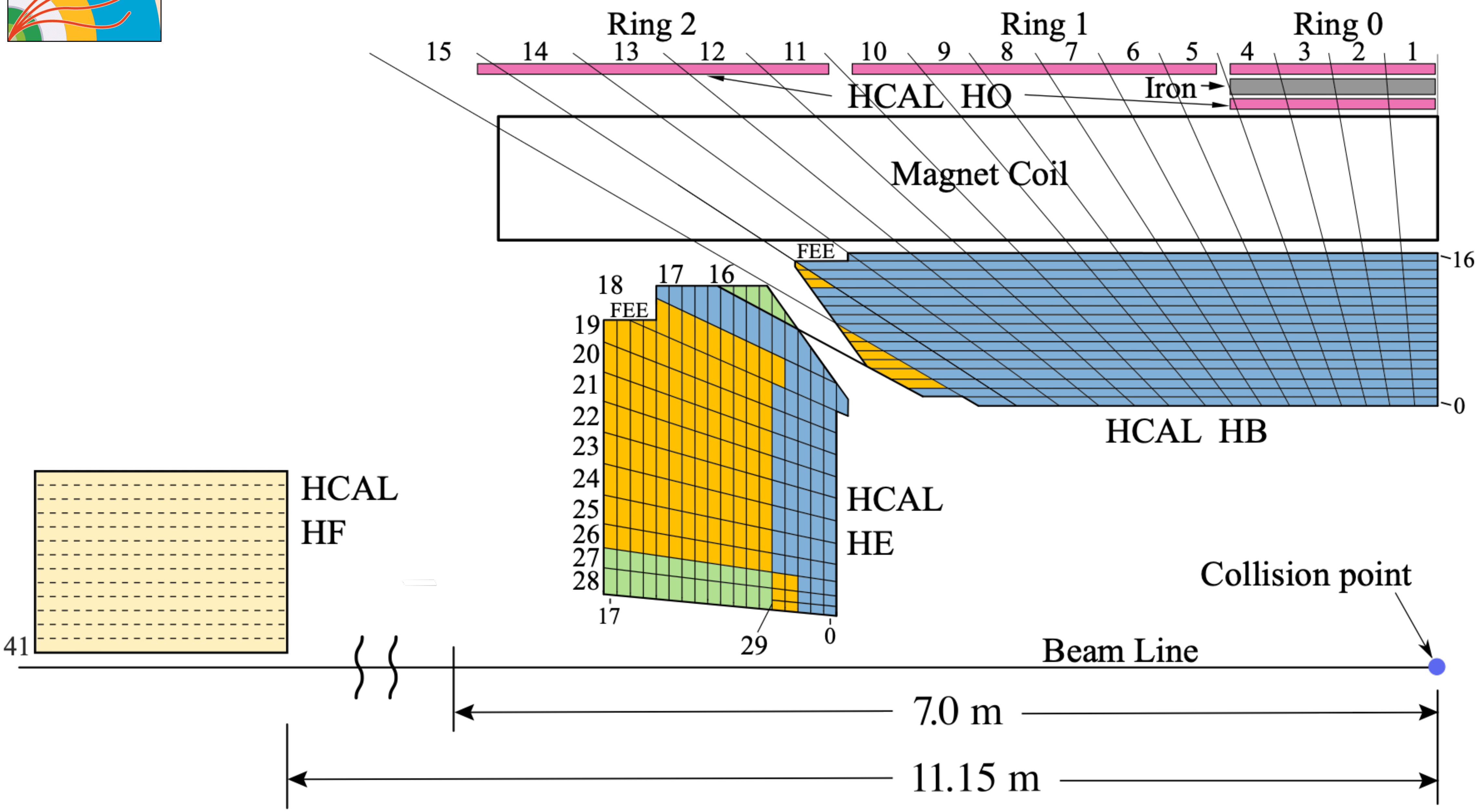
Outline

- Introduction
- CMS Hadron Calorimeter
- Inter-calibration of Barrel and Endcap
- Absolute calibration of Barrel and Endcap
- Calibration of the forward calorimeter
- Calibration of the outer hadron calorimeter
- Summary

Introduction

- The hadron calorimeter in the CMS experiment is crucial for a precise measurement of jet energies and missing transverse energy
- Precision tests of the Standard Model requires accurate determination of these quantities
- The hadron calorimeter was initially calibrated using data from several dedicated test beam experiments and using signals from a number of built-in calibration system based on laser or rdaioactive source
- These measurements are improved through the analysis of Cosmic Ray data
- Use information from collision data to further improve the precision of calibration

Hadron Calorimeter of CMS



- The hadron calorimeter has 4 major components: barrel (HB), endcap (HE), forward (HF), outer (HO)
- HB, HE, HO makes use of layers of plastic scintillators in brass absorbers with light transferred through fibers to HPD's and digitized by charge integration devices (QIE)
- HF uses quartz fibers in steel absorbers and the Cerenkov light is read out using PMT's

Energy Determination and Calibration

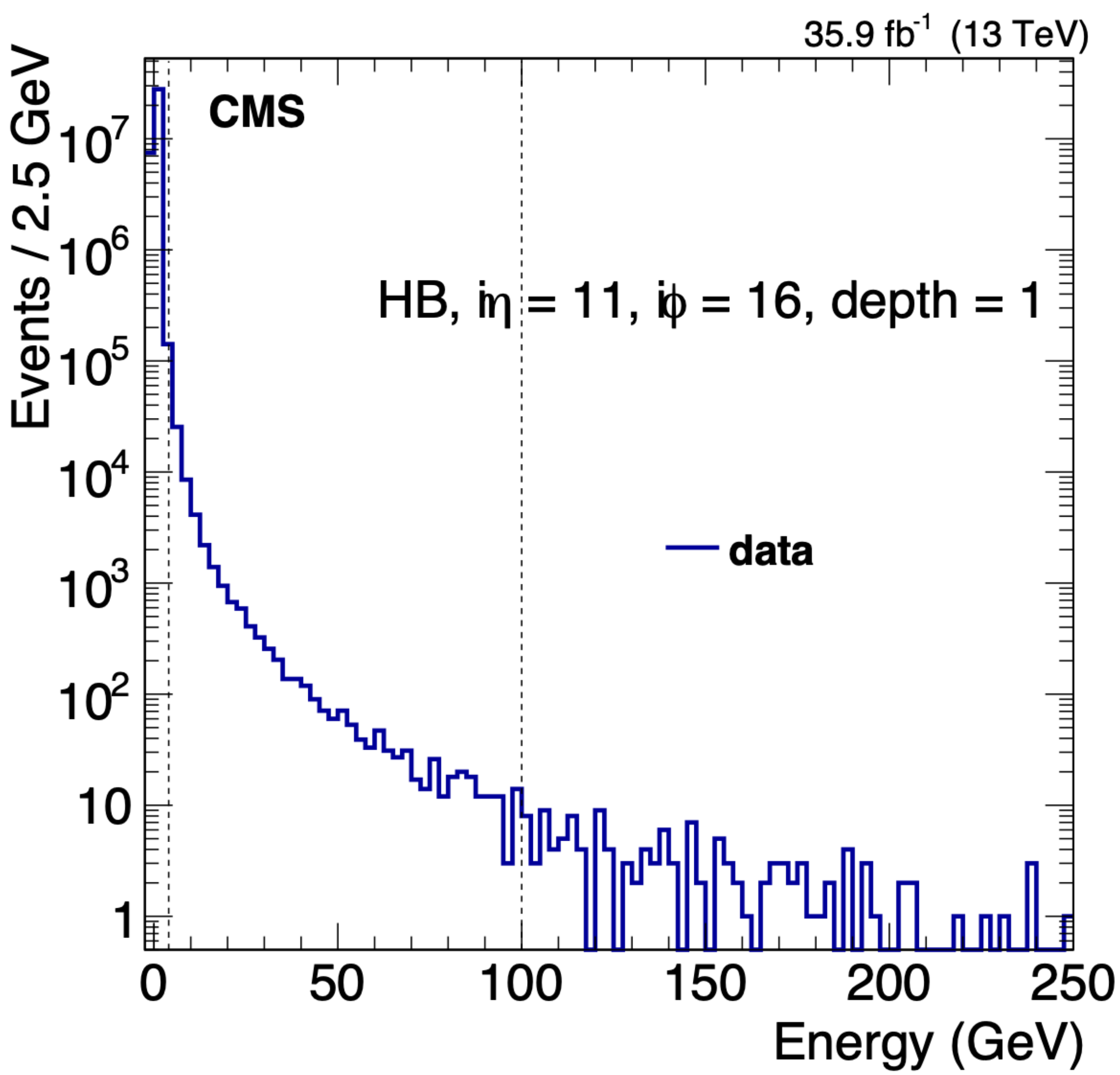
- Charge in the QIE's are integrated in 25 ns time slices and energy reconstruction in the 4 HCAL sub-detectors is done taking care
  - choice of optimum number of time slices
  - reduction the effect of pileups
  - compensation the effect due to radiation damage
  - utilization of the reconstructed calorimeter energies in the physics objects

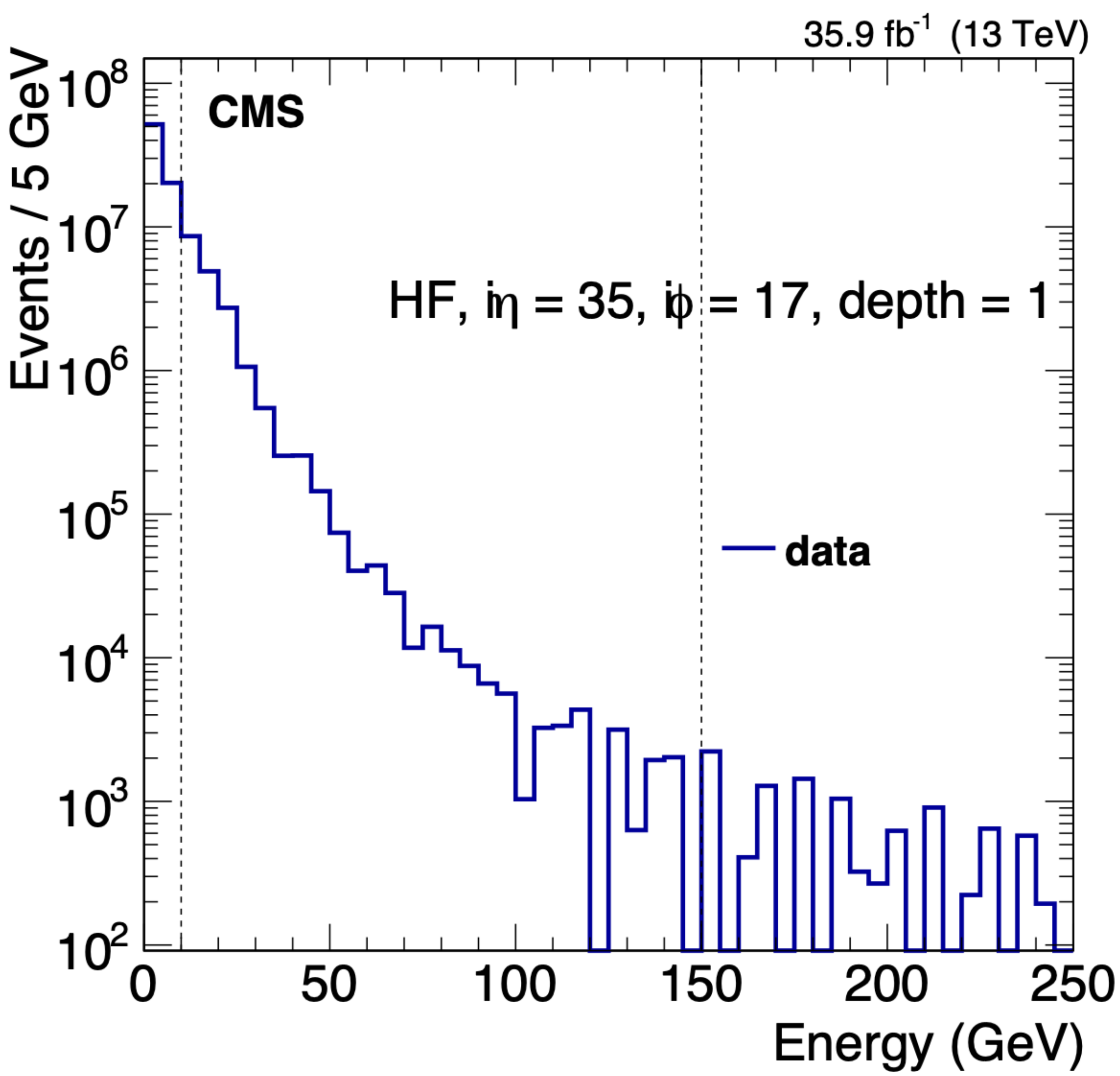
- Use 35.9 fb^{-1} collision data collected during 2016 at 13 TeV

- Calibration is carried out in several steps
  - Inter-calibration of HB, HE, HF utilizing azimuthal symmetry in minimum bias events
    - Use an iterative method
    - Use method of moments
  - Absolute calibration of HB, HE using isolated charged hadrons of momenta between 40-60 GeV
  - Absolute calibration of HF using events of the type $Z \rightarrow e^+e^-$
  - Inter-calibration and absolute calibration of HO using muons and di-jet events

Azimuthal Symmetry (Iterative Method)

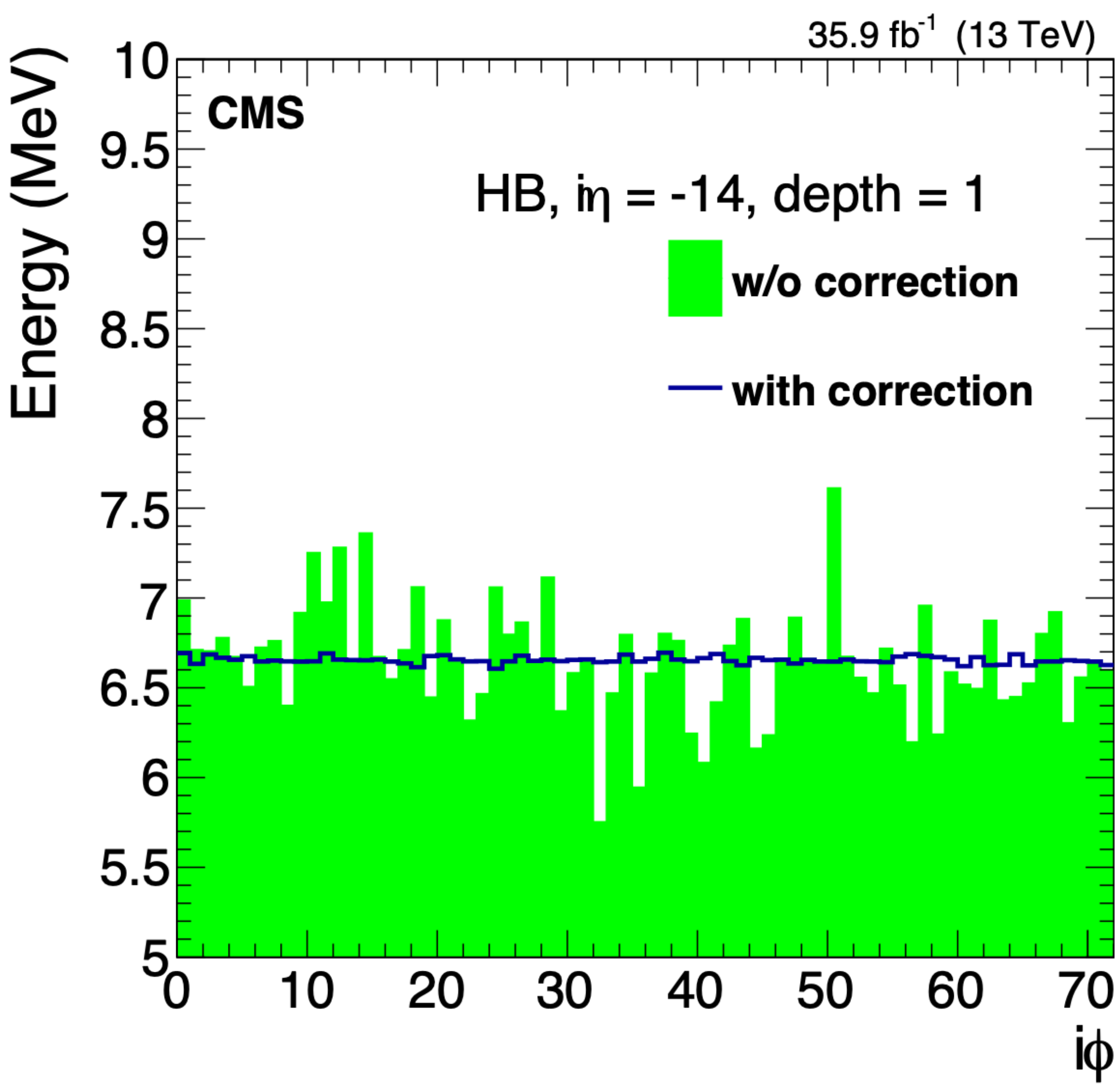
- Equalize mean of the energies among all the iϕ channels for a given iη and depth
- Use data triggered by ECAL or Muon system
- Choose a range of energies depending on sub-detector type
  - avoid influence of noise
  - avoid influence of accidental high energy hits

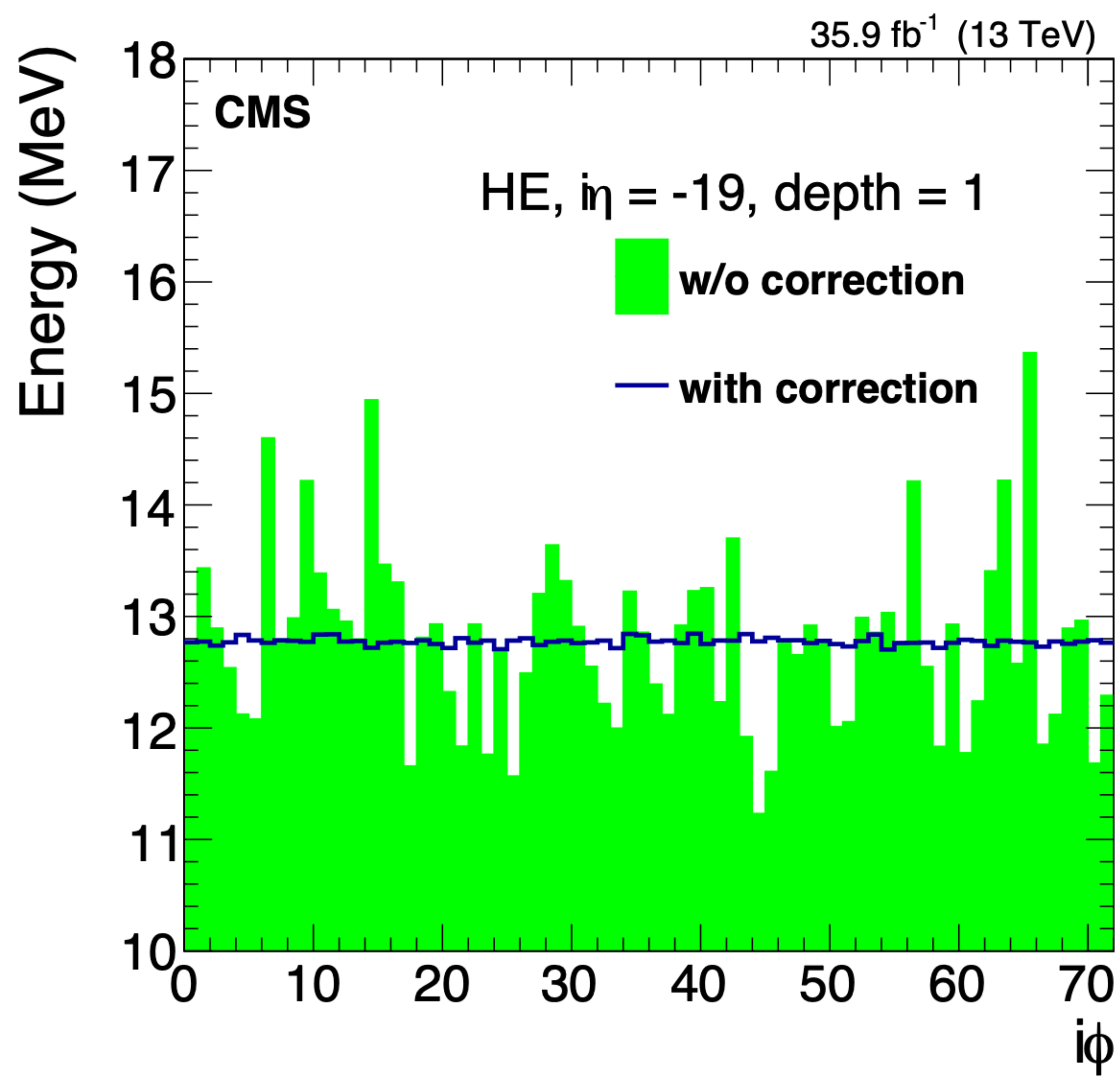




Azimuthal Symmetry (Iterative Method)

- Measure total energy in the range $$E_{\text{tot}} = \int_{E_{\text{low}}}^{E_{\text{high}}} \frac{\mathrm{d}N(E)}{\mathrm{d}E} E \mathrm{d}E$$
- Obtain correction factors which equalize $\langle E_{Tot} \rangle$ in all iϕ channels
- Apply this correction factor, re-evaluate if the threshold criteria are satisfied and obtain a new set of correction factor
- Iterate till the procedure converges
- Statistical accuracy: ~1% for HB, ~0.5% for HF, 0.1-1.0% for HE



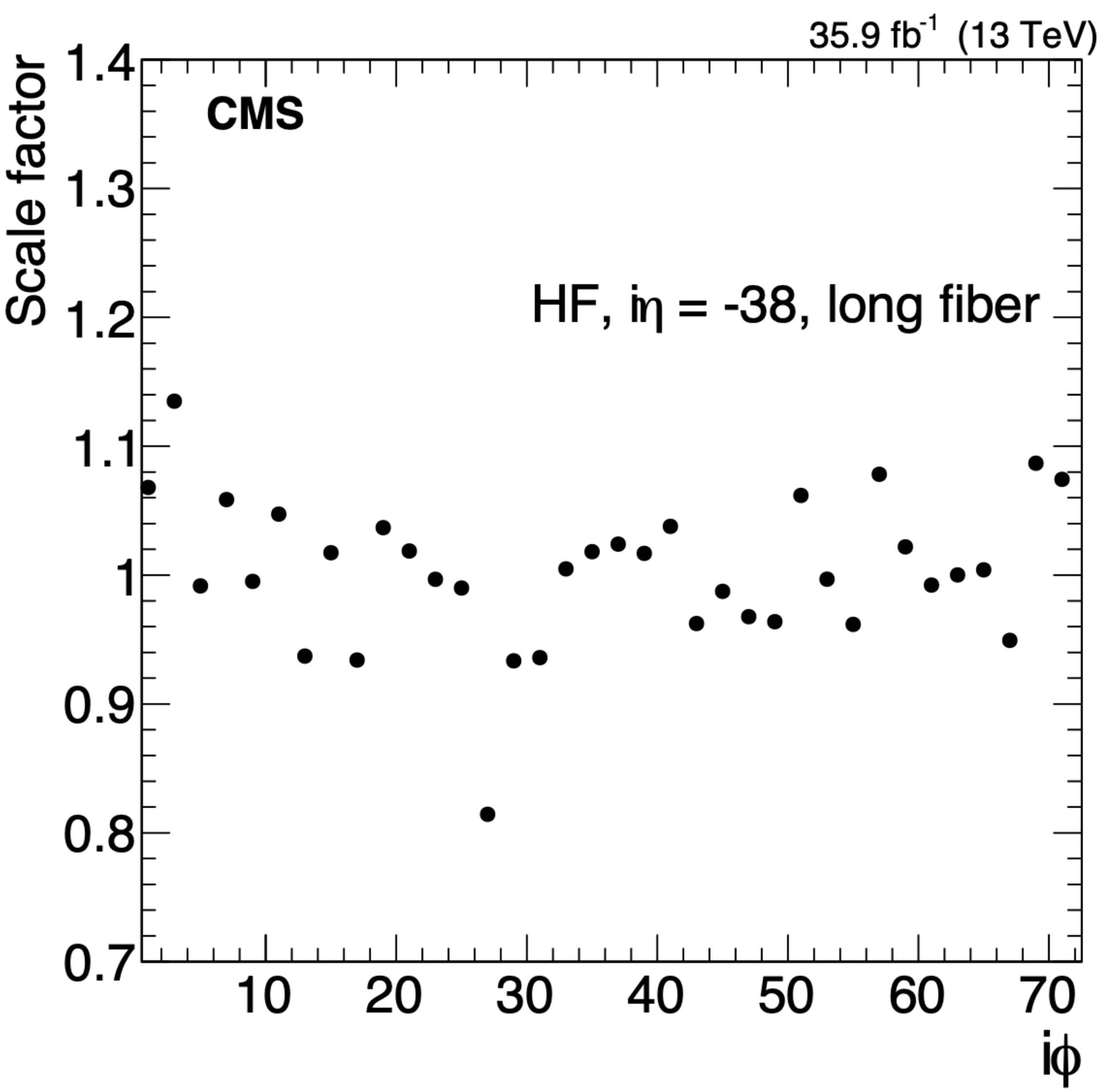


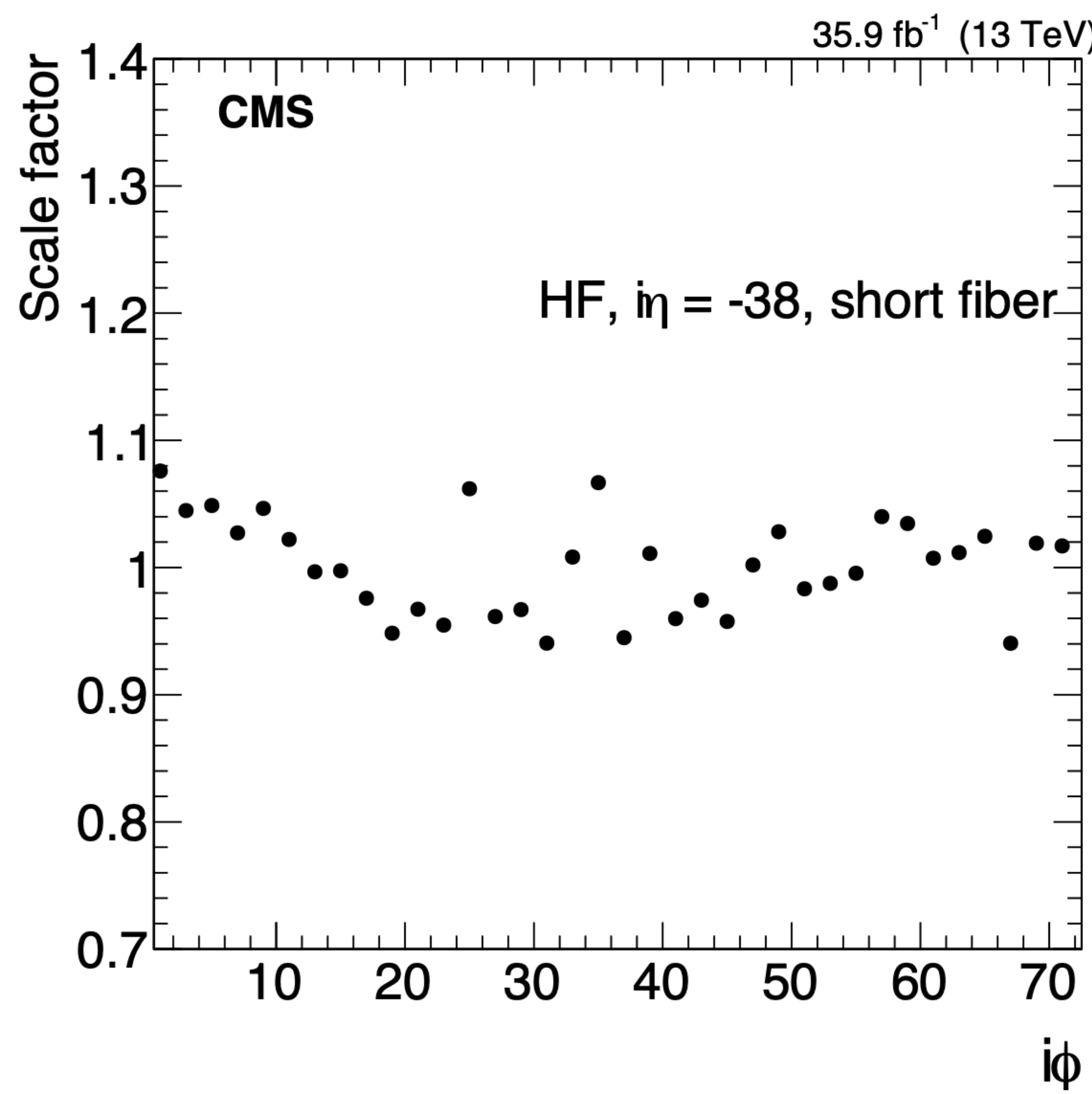
Azimuthal Symmetry (method of moments)

- Use non-zero suppressed data (all level 1 accepts scaled by 4096)
- Utilize the two central moments:

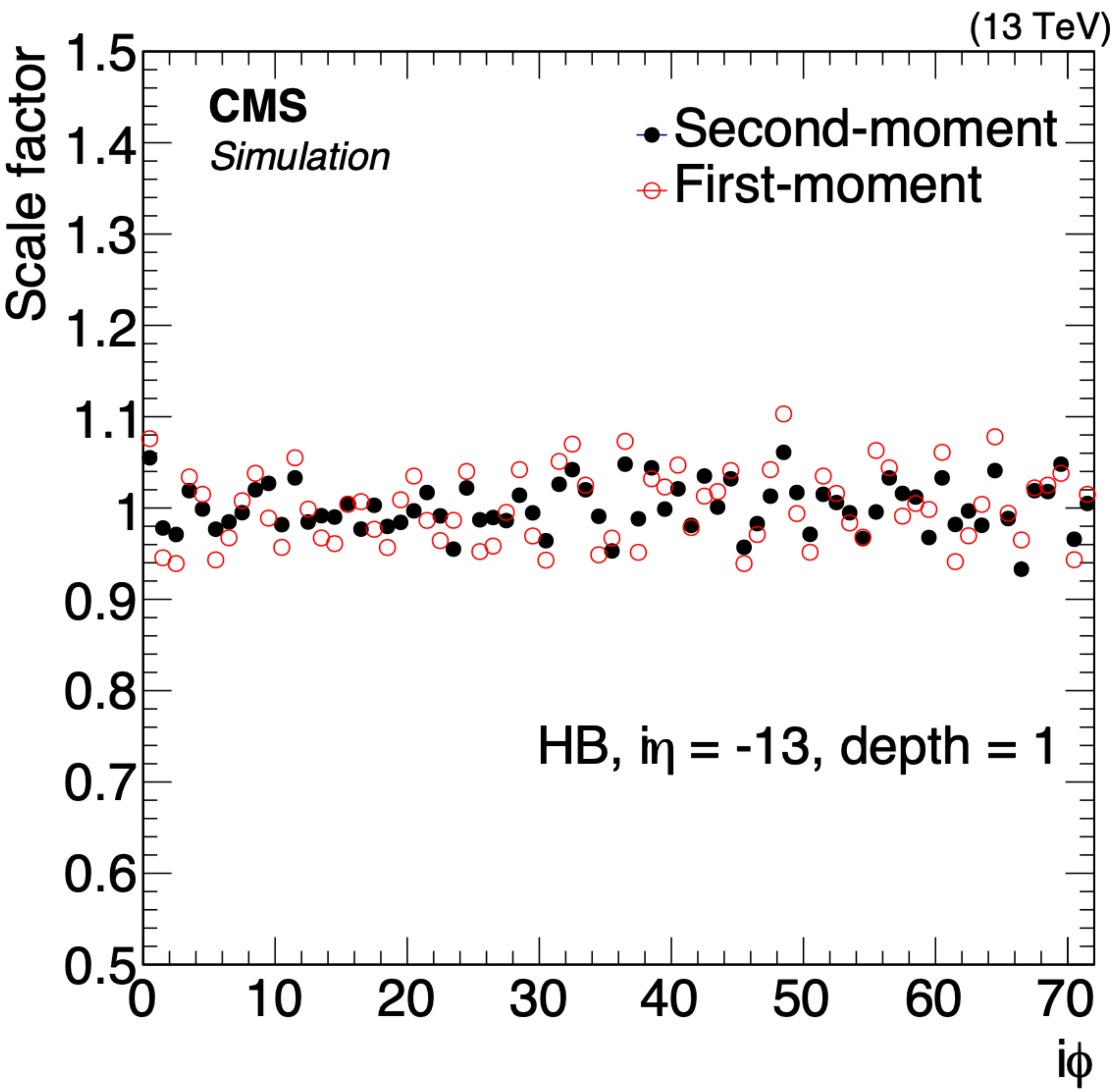
$$C_{i\eta,i\phi} = \frac{\langle E_{i\eta,i\phi}\rangle}{\frac{1}{N_\phi}\sum_{j\phi}\langle E_{i\eta,j\phi}\rangle} \qquad C_{i\eta,i\phi} = \sqrt{\frac{\frac{1}{N_\phi}\sum_{j\phi}\Delta^2 R_{i\eta,j\phi}}{\Delta^2 R_{i\eta,i\phi}}}$$

- Need pedestal data to separate signal from noise
- Noise data not available for HF → use first central moment



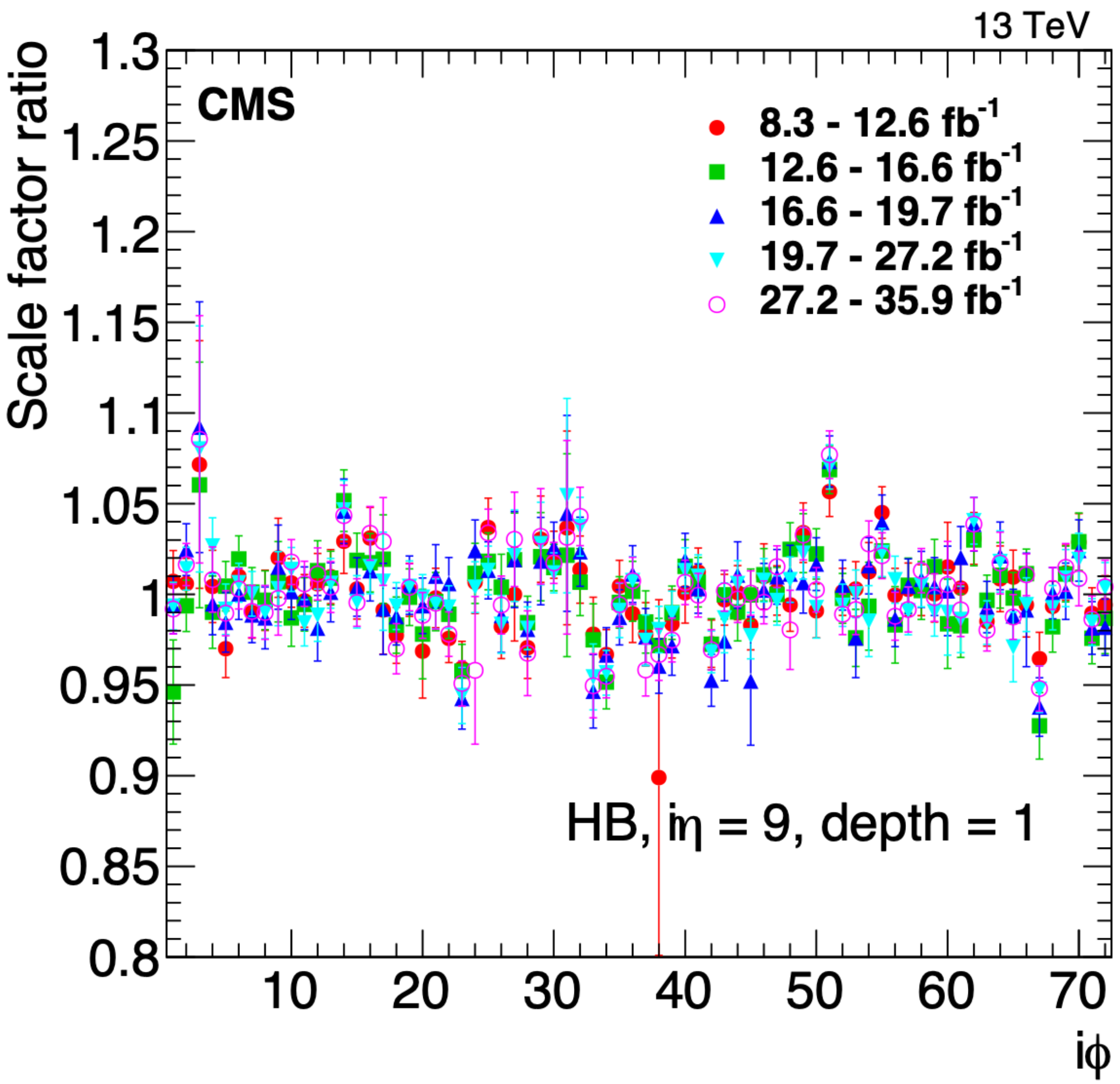


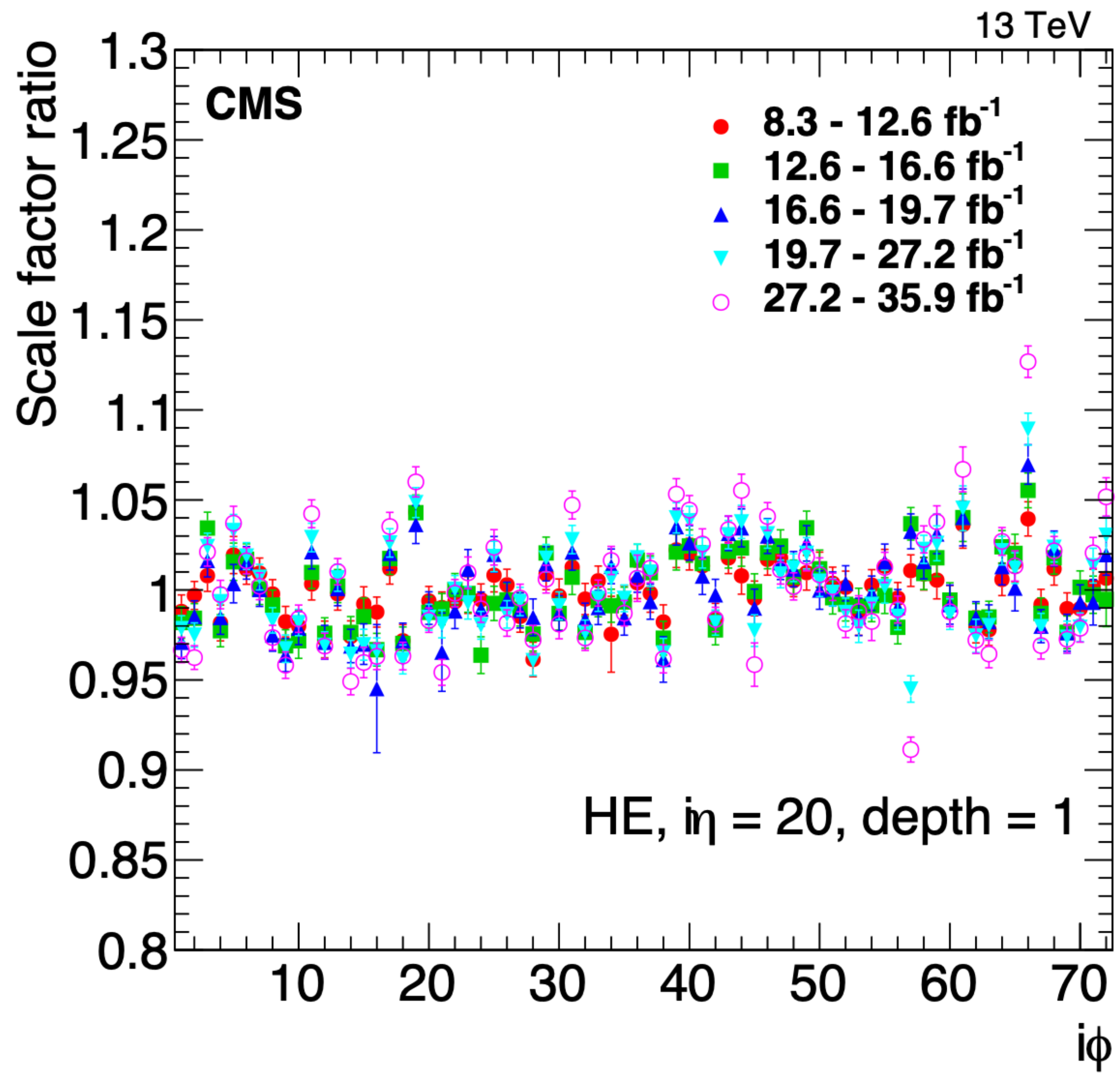
Consistency of using first or second moments



- Usage of either of the two moments provides consistent set of correction factors
- With similar statistics the second central moments lead to smaller uncertainties
- For HB and HE 2nd method of moments are used

Azimuthal Symmetry (method of moments)

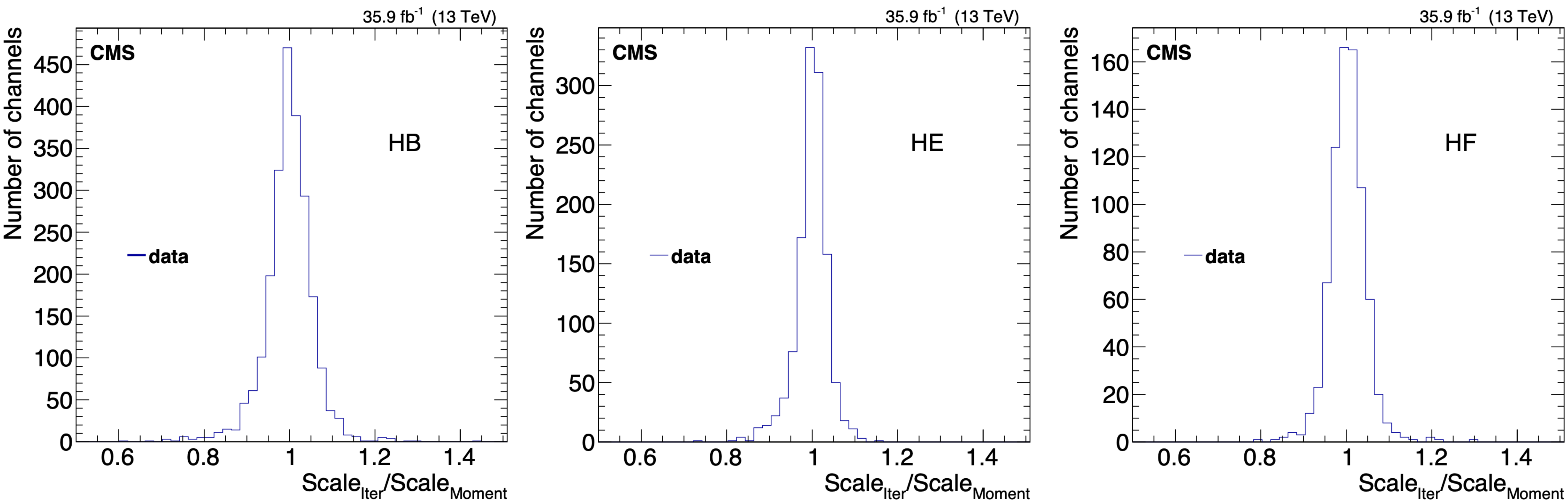




- Second central moment is used for HB and HE
- 2% statistical accuracy is achieved with few million events
- Study the stability of the correction factors over the year

Azimuthal Symmetry (combine 2 methods)

- Results of the two methods agree within a few percent
- Combine the two set of factors and use that as the final correction factors



Calibration using isolated tracks

- Use charged hadrons of momentum between 40 and 60 GeV
- Propagate to calorimeter surface and check if it is isolated with respect to other charged particles on the HCAL surface
- Demand the energy in ECAL corresponding to the track is below 1 GeV
- Momentum is accurately measured in the tracker
- Demand the response:

$$E_{\mathrm{HCAL}} / (p_{\mathrm{track}} - E_{\mathrm{ECAL}})$$

to peak at 1 (fit to a Gaussian distribution to get the most probable value)

- Two sources of data:
  - use a dedicated HLT seeded by jet trigger at L1 and demanding charge isolation with pixel tracks
  - use an offline filter to two primary data streams triggered by EGamma and Jet triggers

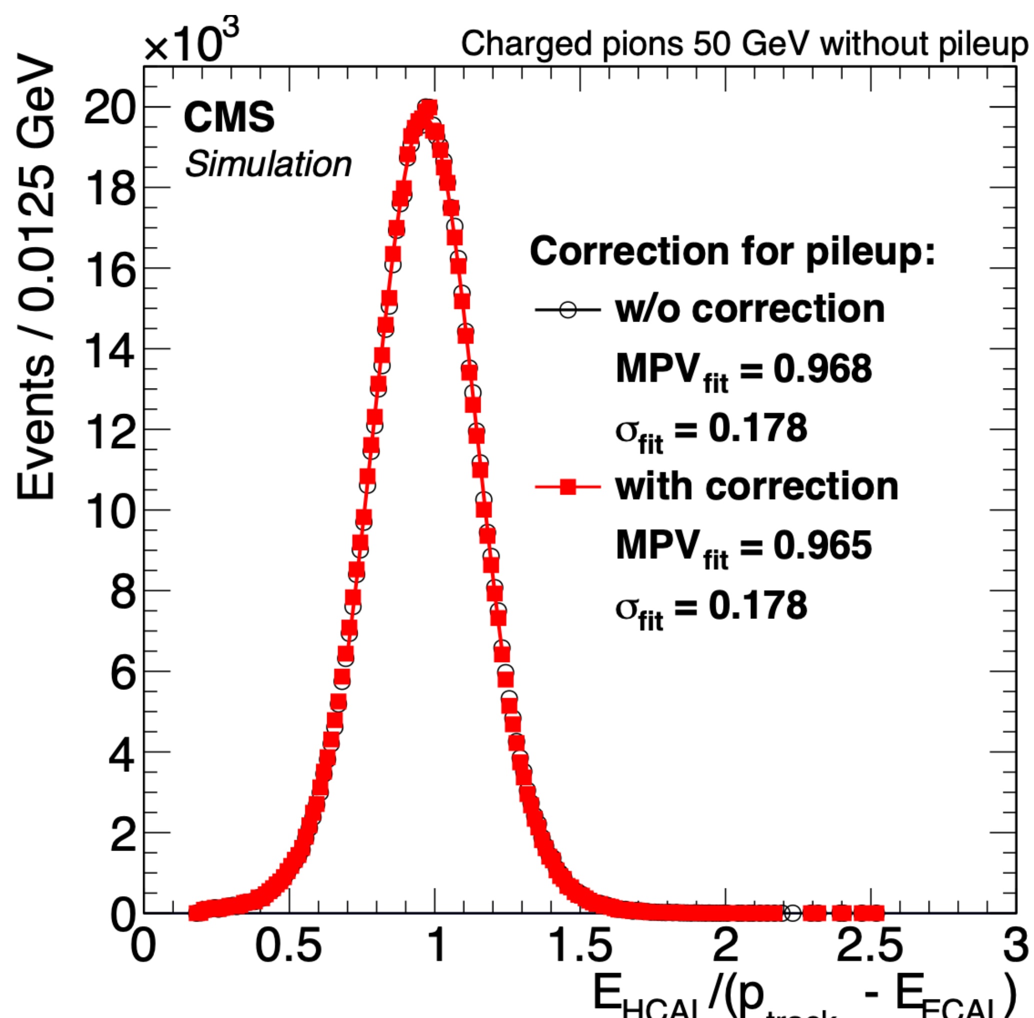
Calibration using isolated tracks

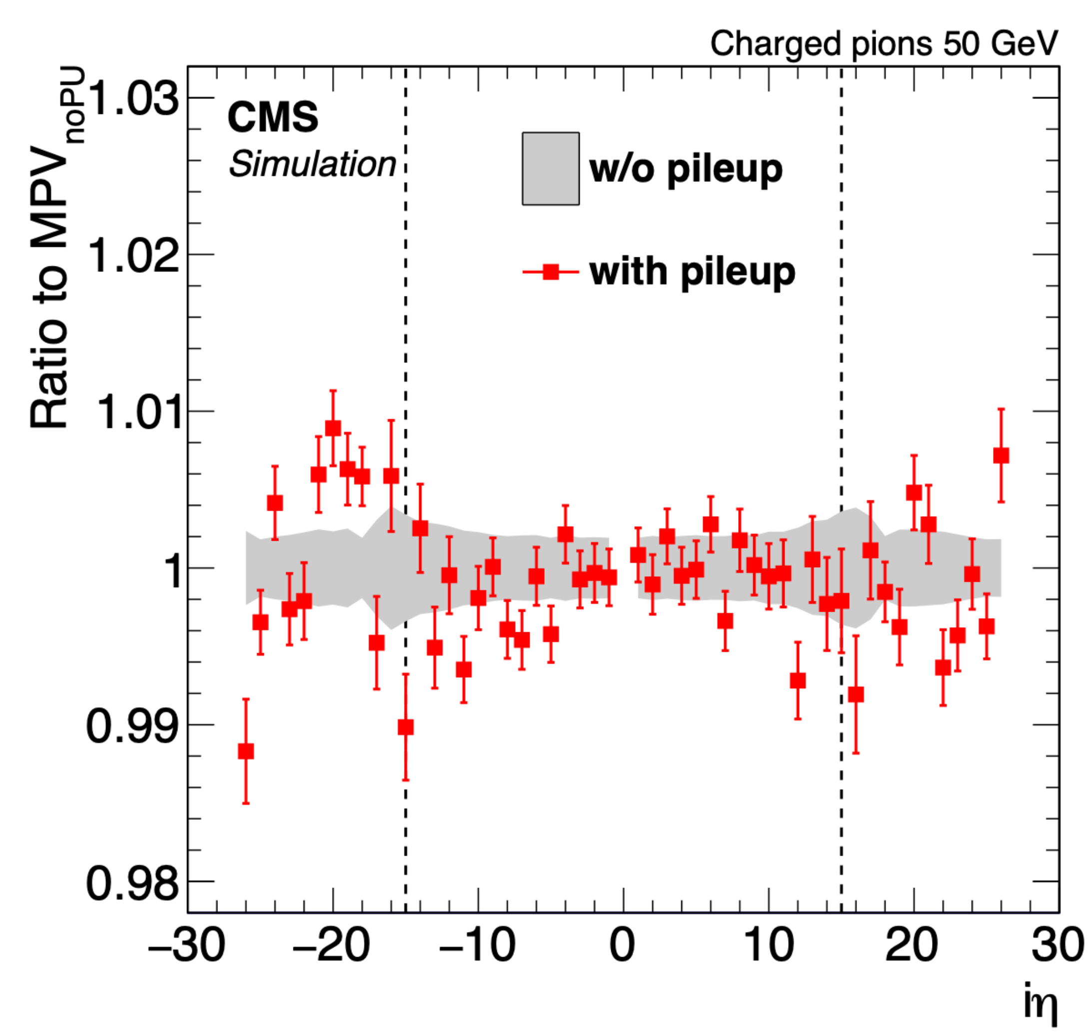
- The contribution due to pile up is subtracted on event-by-event basis using energy in an angular cone surrounding the isolated track

$$E_{\mathrm{cor}} = E\left(1 + a_1 \frac{E}{p}\left(\frac{\Delta}{p} + a_2\left(\frac{\Delta}{p}\right)^2\right)\right)$$

$$(a_1, a_2) = \begin{cases} (-0.35, -0.65) & \text{for } |i\eta| < 25, \\ (-0.35, -0.30) & \text{for } |i\eta| = 25, \\ (-0.45, -0.10) & \text{for } |i\eta| > 25, \end{cases}$$

estimated from MC and validated using independent MC sample





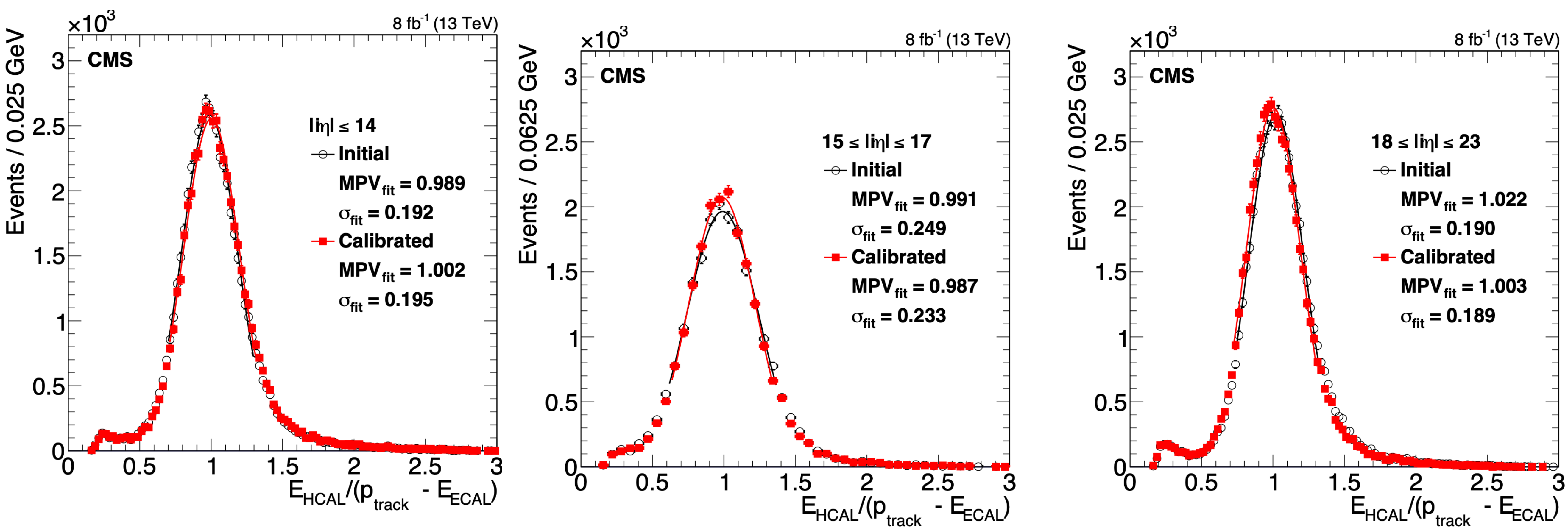
Calibration using isolated tracks

- Use an iterative method to get the correction factor

$$c_i^{(m+1)} = c_i^{(m)} \left(1 - \frac{\sum_j w_{ij}^{(m)} \left(\frac{E_j^{(m)}}{p_j - E_{j,\mathrm{ECAL}}} - \mathrm{RR} \right)}{\sum_j w_{ij}^{(m)}} \right)$$

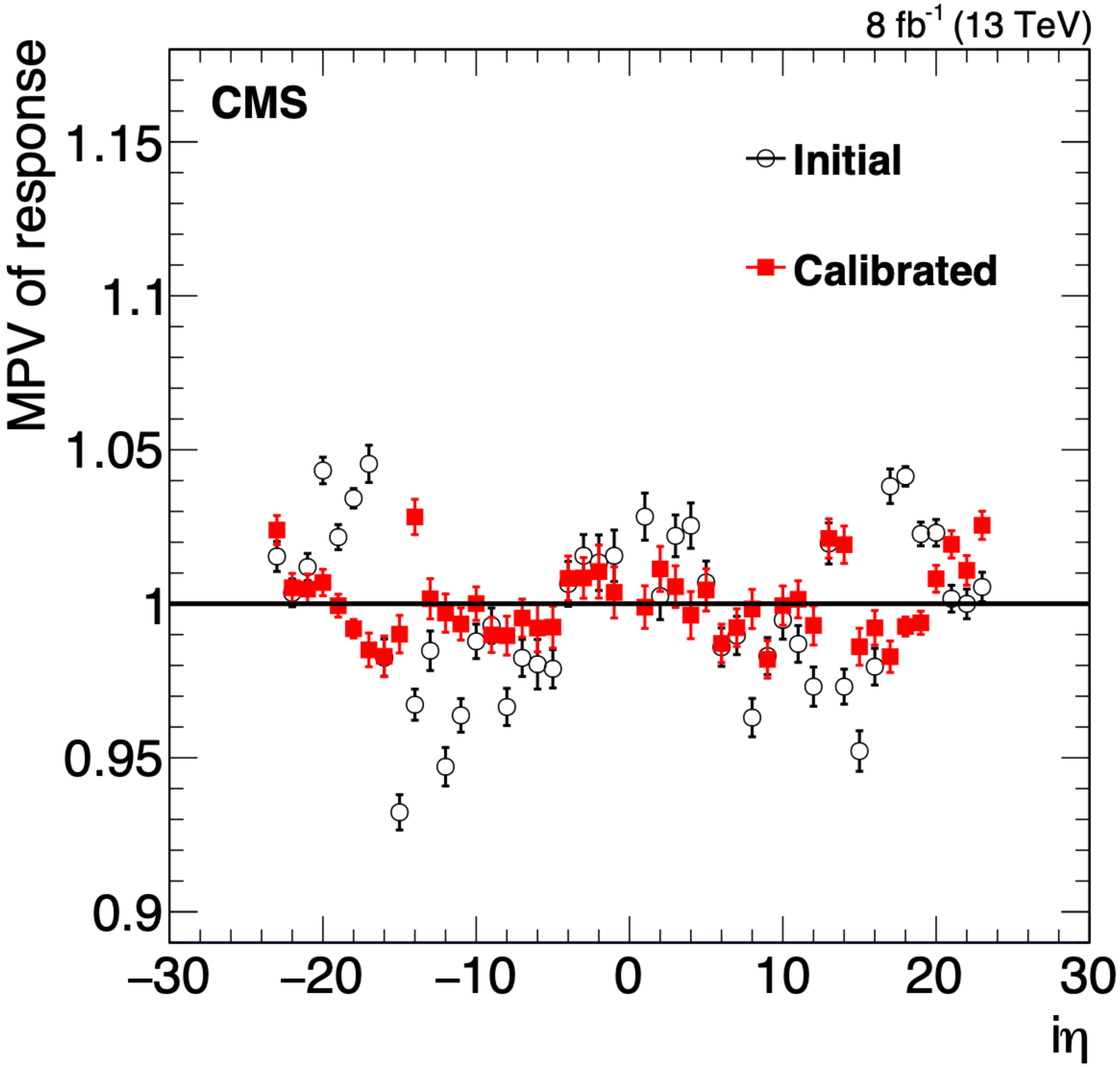
where

$$w_{ij}^{(m)} = \frac{c_i^{(m)} \cdot e_{ij}}{E_j^{(m)}}, \qquad E_j^{(m)} = \sum_{i=1}^{n_j} c_i^{(m)} \cdot e_{ij} \qquad \mathrm{RR} = \mathrm{mean}_{\mathrm{sample}} / \mathrm{mode}_{\mathrm{sample}}$$



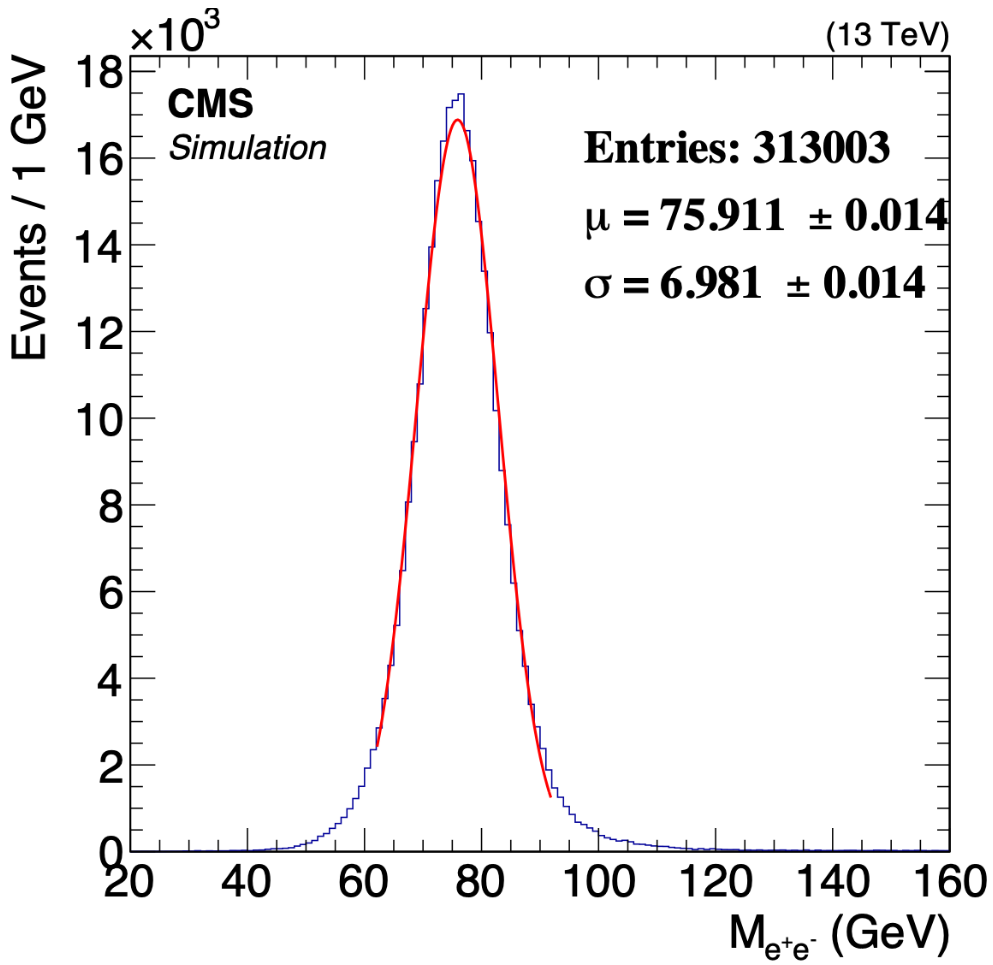
Calibration using isolated tracks

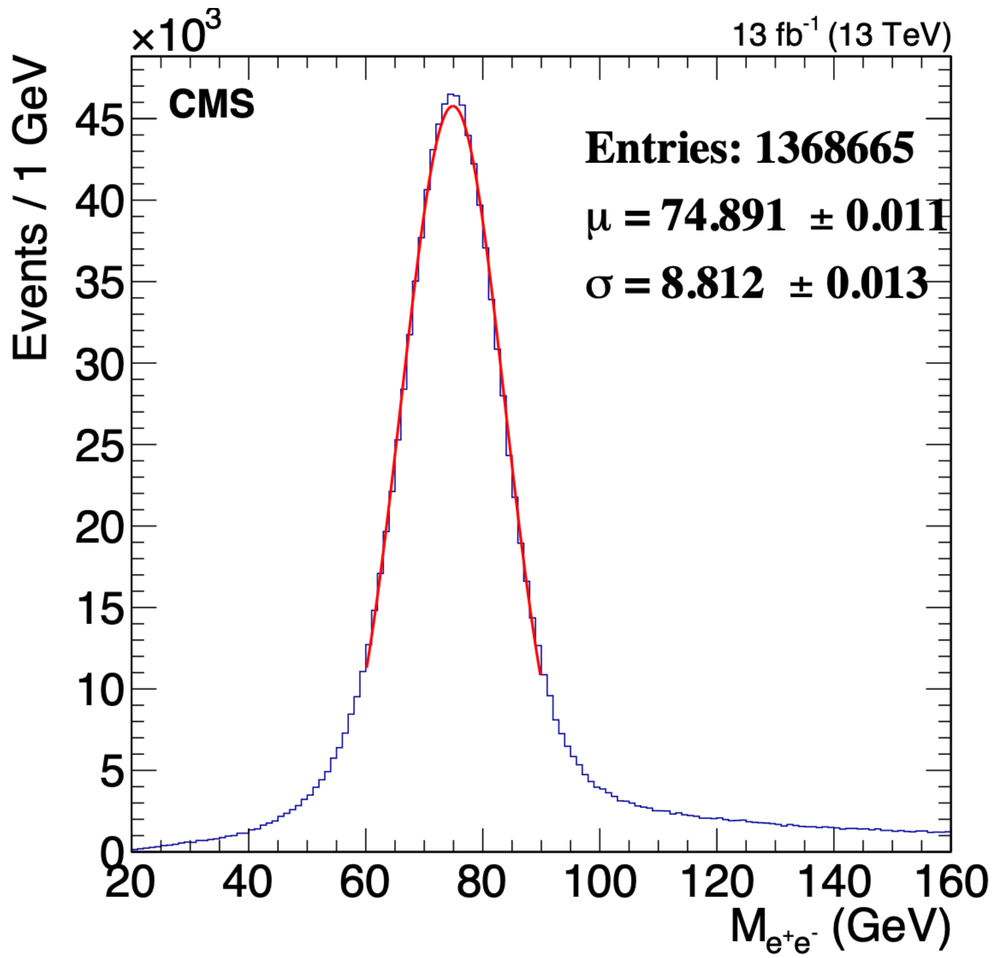
- Equalization is achieved within ±2.5% for channels with |iη| ≤ 23.
- Statistical accuracy of ~2% achieved



Calibration of HF using Z → e^+e^- events

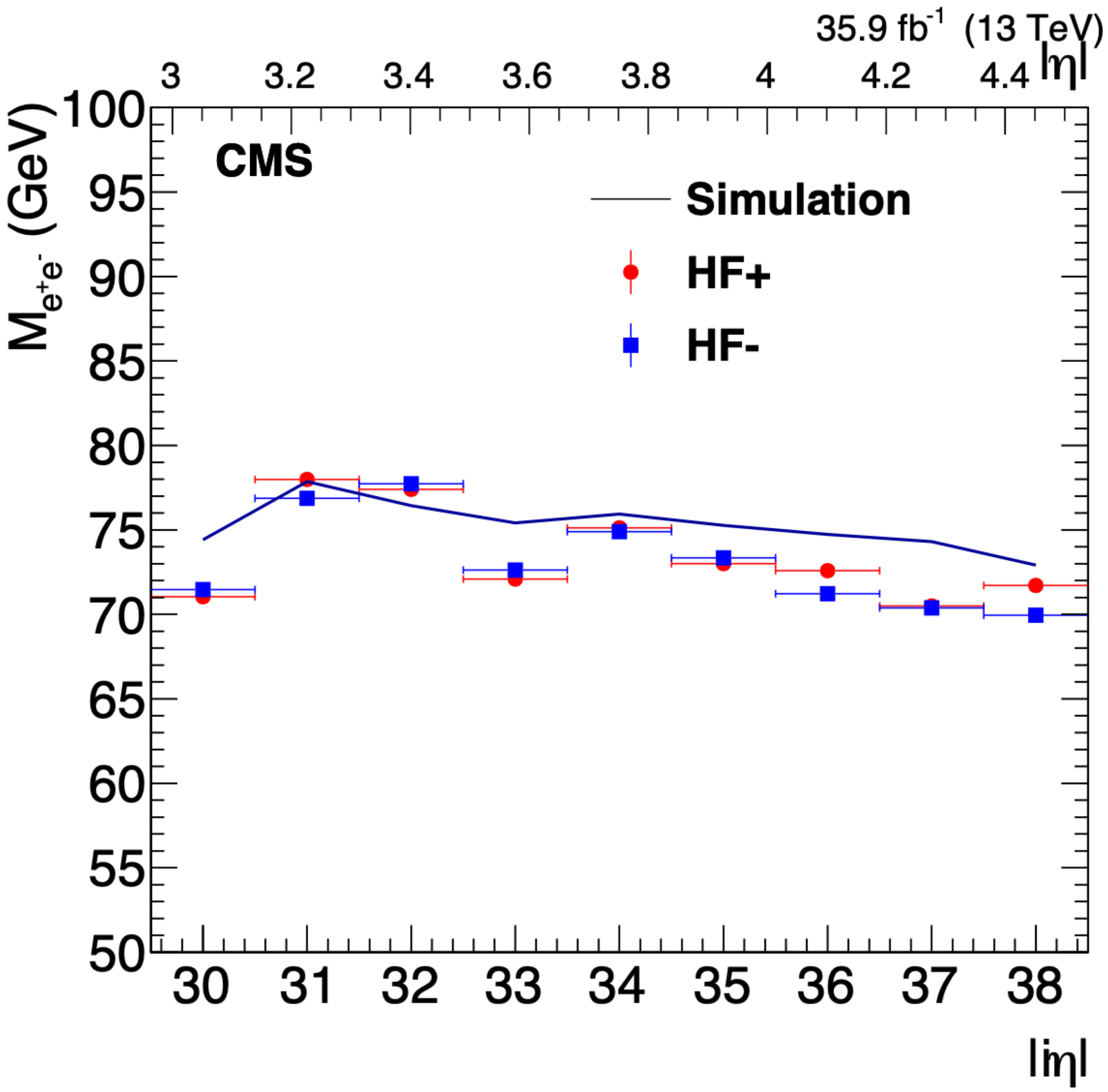
- Utilize Z → e^+e^- events where one of the electrons is measured in the ECAL and the other in HF
- Use standard physics channel (miniAOD) and PF electron candidates
- Require isolated electron candidate in ECAL and in HF with p_T thresholds of 25 GeV and 15 GeV respectively

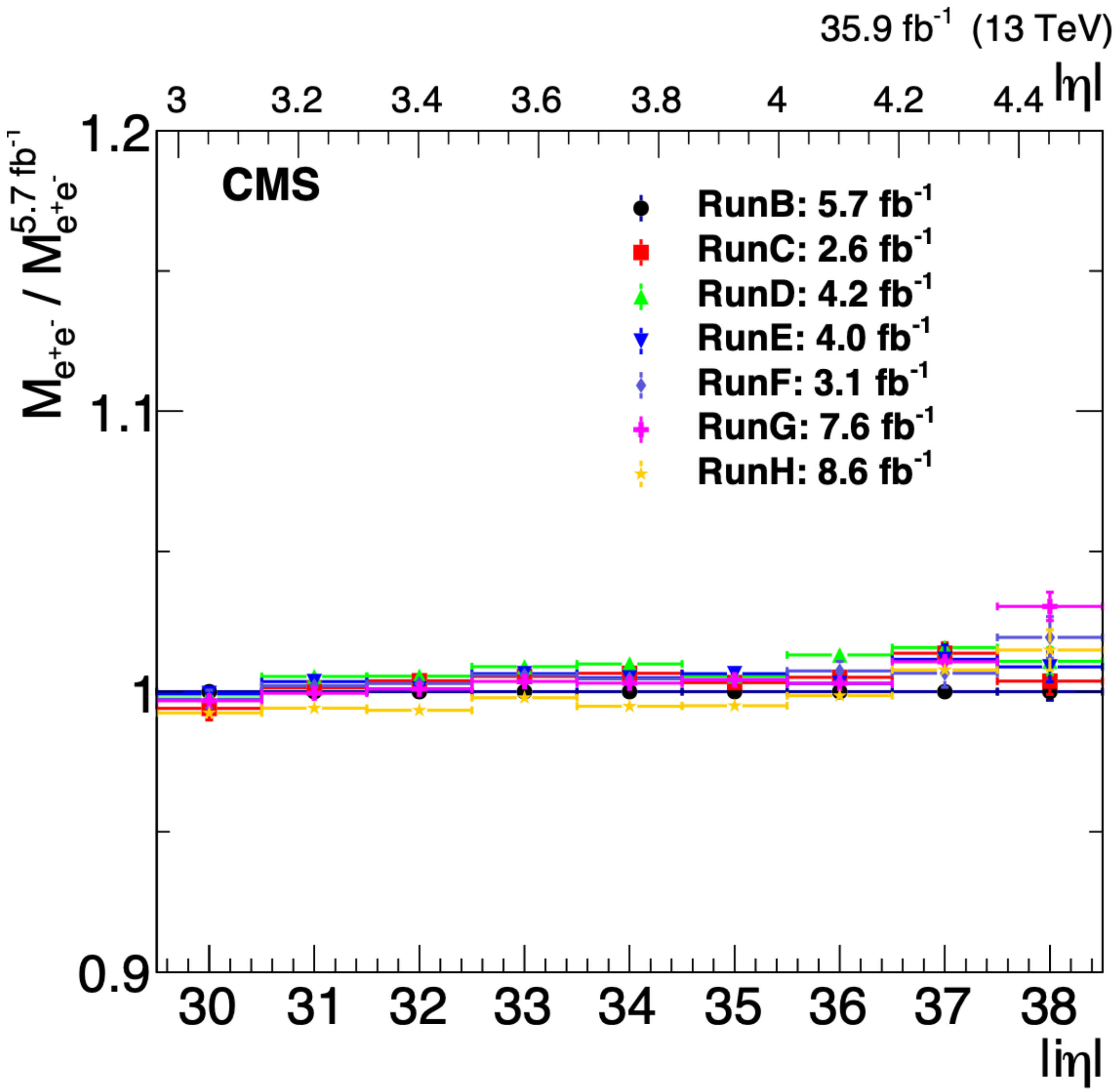




- Use only long fiber energy and lack of containment correction results the Z peak at a value lower than nominal mass (in MC as well as data)

Calibration of HF using Z → e^+e^- events

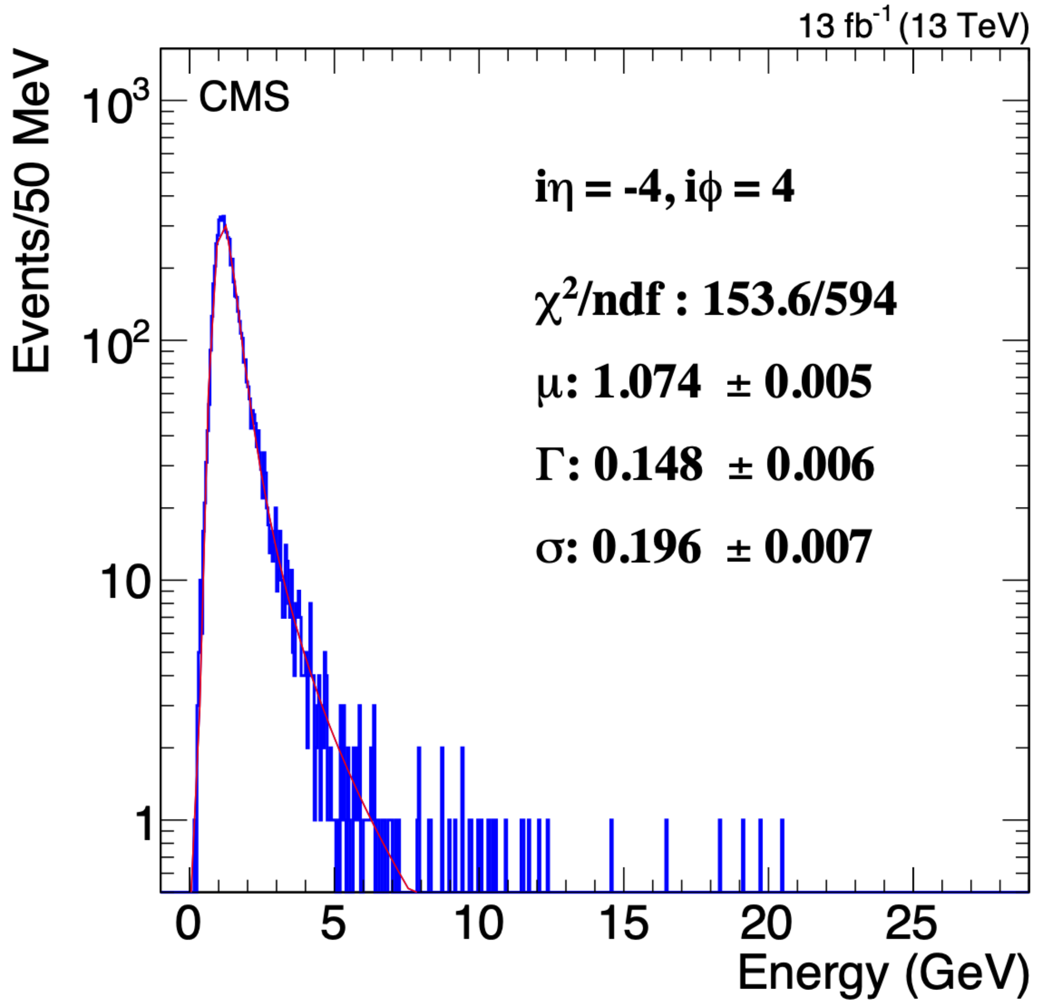


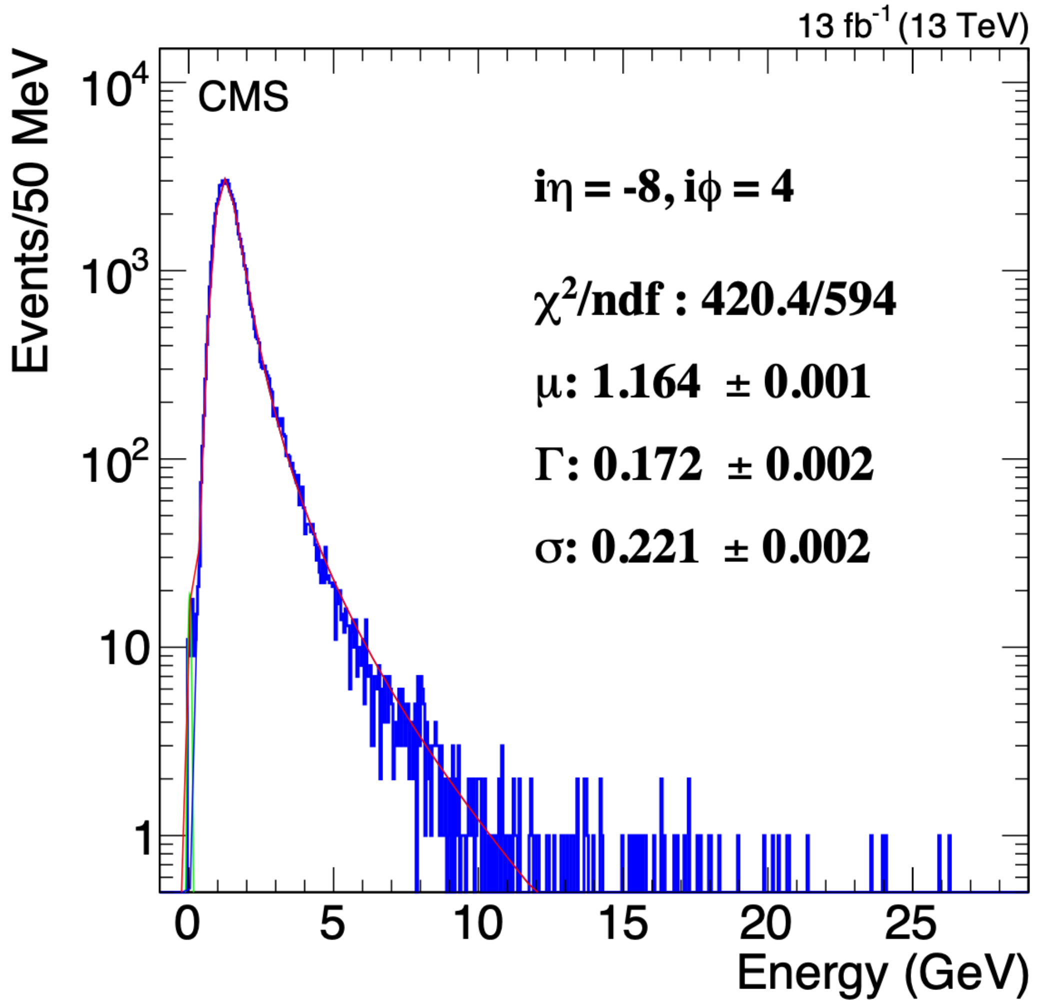


- The HF energy response for HF+ and HF- is the same within uncertainties in both simulation and data.
- For the towers with |iη| = 33:38, the data has a lower energy scale than simulation

Calibration of the Outer Hadron Calorimeter

- Use reconstructed muons from collision data with a dedicated offline selection procedure from SingleMuon data stream
- Extrapolate muon to the HO surface and demand
  - cut on muon p_T depending on η of the muon
  - isolation at the HO surface
  - good timing measurement in the HO hit
- Get MPV using Gaussian convoluted Landau distribution and equalize response after path length correction





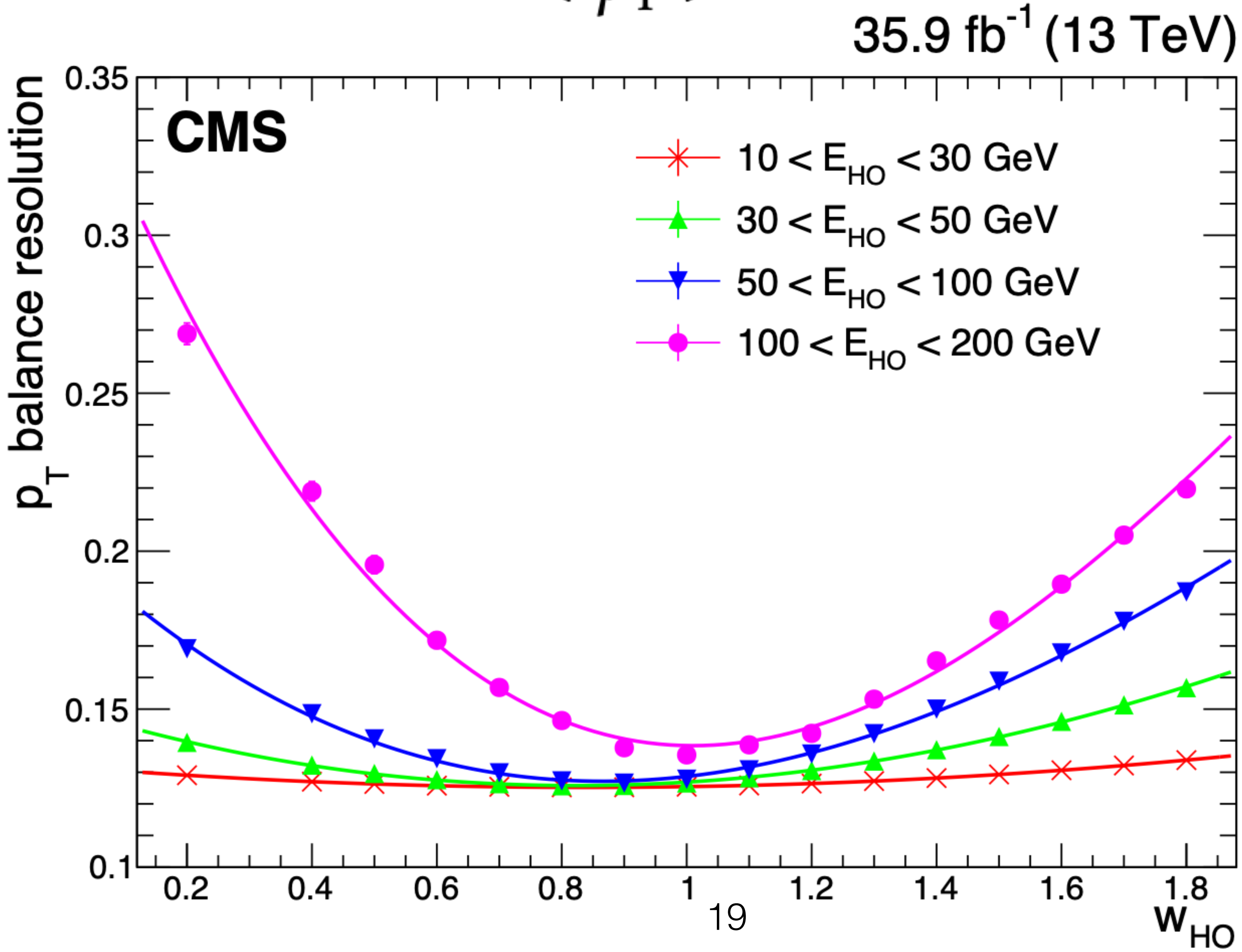
Calibration of the Outer Hadron Calorimeter

- Jet energy is determined from energies in ECAL, HCAL, using w_{HO}

$$E_{Jet} = E_{ECAL} + w_{HCAL} \times (E_{HB} + w_{HO} \times E_{HO})$$

- w_{HO} is determined from a study of p_T balance in di-jet events

$$\frac{(p_{T1} - p_{T2})}{< p_T >}$$



Summary

- CMS utilizes a variety of data to calibrate the energy measurements obtained from its hadron calorimeter

- Mean noise level of all channels are monitored for each fill of LHC and scale factors are checked for each run period

- HB, HE, HF makes use of azimuthal symmetry of energy flow in minimum bias events for inter-calibration of the channels, while HO uses muons for inter-calibration

- Absolute energy scales in HB, HE are determined using isolated charged hadrons. Energy scale in HF is determined from events of the topology $Z \to e^+e^-$. Absolute scale in HO utilizes p_T balance in di-jet events

- Using 35.9 fb^{-1} collision data at 13 TeV, calibration constants are determined with systematic uncertainty of 3% for inter-calibration and 2% for absolute calibration

Additional Slides

Consistency of using first or second moments

- Usage of either of the two moments provides consistent set of correction factors
- With similar statistics the second central moments lead to smaller uncertainties
- The structure is due to materials in front of the calorimeter